

# MAGNETIC SENSORS PROJECT

Dr. Ted R. Clem

Code R22 Coastal Systems Station, Dahlgren Division

Naval Surface Warfare Center, Panama City, FL 32407-7001

Phone: (904)234-4670 Fax: (904)235-5462 Email: clem\_ted@ccmail.ncsc.navy.mil

## LONG-TERM GOAL

Clandestine mine reconnaissance is the Navy's highest MCM priority. During the 1980's, the Superconducting Gradiometer/Magnetometer Sensor (SGMS) was demonstrated in the Magnetic and Acoustic Detection of Mines (MADOM) ATD to provide effective detection/classification capabilities, especially against buried mines, and to reduce significantly acoustic false alarms arising from bottom clutter [1], [2]. This sensor utilized the low critical temperature (low  $T_c$ ) superconductor niobium and required liquid helium for sensor cooling. Advanced magnetic sensor approaches are being developed to transition this technology to the fleet.

## TECHNOLOGY OBJECTIVES

The current focus of this project is to develop an advanced High  $T_c$  Superconducting Gradiometer (HTSG) prototype cooled by liquid nitrogen in order to attain long detection ranges in substantially reduced package sizes with minimal cryogen support requirements and to demonstrate it at sea in FY 1999.

## APPROACH

The technical approach for this project involves the following phased efforts: (1) preliminary sensor concept design, (2) development and laboratory evaluation of key sensor components, (3) sensor development, (4) sensor evaluation in motion studies simulating underwater and airborne tow operation, and (5) sensor at-sea testing. In FY 1997 work focused on high- $T_c$  exploratory development including initial evaluation of a HTSG laboratory prototype, the design of a fully populated 5-channel low  $T_c$  Thin Film Gradiometer (TFG), and development of an electronics assembly for field deployment of either the HTSG or TFG prototypes.

## WORK COMPLETED

*Advanced Superconducting Device Development:* In FY 1997, significant progress was made in the fabrication of high- $T_c$  devices with multi-layer features to duplicate capabilities comparable to niobium thin-film technology. A gradiometer circuit with monolithic thin-film loops providing common-mode signal subtraction prior to signal amplification by a Superconducting Quantum Interference Device (SQUID) demonstrated a sensitivity of 54 picotesla/meter-Hertz<sup>1/2</sup> (pT/m-Hz<sup>1/2</sup>) at 1 Hz. This represents one of the best results reported for such a device [3]. Although this performance falls short of the sensitivity required for the naval applications under consideration, such advances are required in the long term to increase sensitivity and to maintain coherence of gradiometers for mobile applications. The impact of flux trapping for unshielded operation of high- $T_c$  sensors in the Earth's magnetic field and approaches to mitigate such effects are being investigated [4]- [6]. Work also continued in FY 1997 in the development of low- $T_c$  niobium thin-film devices with device yield increased from 10 to over 50%.

*Development of a HTSG Sensor Prototype:* In order to circumvent the current limitations in high- $T_c$  fabrication technology mentioned above, a HTSG sensor approach is being pursued which features the three-sensor gradiometer concept [7]. This three-sensor concept recently has been pursued successfully using room-temperature fluxgate magnetometers demonstrating a sensitivity better than 300 pT/m-Hz<sup>1/2</sup> at 0.1 Hz in motion [8]. 100-fold increases in sensitivity are being pursued using the high- $T_c$  SQUID magnetometers in place of fluxgate magnetometers. In FY 1997 assembly of a laboratory test article of this HTSG concept was completed. The sensor's white noise stationary was measured at 0.3 pT/m-Hz<sup>1/2</sup>. Work will continue in FY 1998 to optimize its low frequency performance stationary and to establish its motion performance in preparation for sensor upgrade to a field-deployable version in FY 1999.

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*Development of a Miniaturized Electronics Assembly for Sensor Field Deployment:* Advanced flux-lock loop (FLL) electronics with a modulation frequency of 16 MHz, 30 to 100 times faster than conventional schemes, has been developed to improve cryogenic signal amplification and electromagnetic immunity. A benchtop version of the FLL electronics has been demonstrated for both low- $T_C$  and high- $T_C$  sensors. The closed-loop bandwidth for this configuration was 1 MHz under laboratory conditions [9]-[11]. A compact field-deployable room-temperature electronics assembly is being developed to replace the benchtop FLL electronics and to provide automated sensor control, signal digitization, and data linking for field deployment of either the low- $T_C$  or the high- $T_C$  sensors. Miniaturization of the electronics into a single integrated unit mounted onto the sensor, which does not limit the sensitivity of the integrated sensor in motion, represents a major undertaking. The design of the electronics architecture and packaging has been established. Prototype elements of preamplifier, analog, and digital electronics have been manufactured and evaluated. Based on the results from the prototype evaluations, complete sets of these electronic units for the field-deployable assembly have been manufactured. A data link to control individual channels and to multiplex their outputs has been designed and is currently being assembled. A single-channel test of these new electronics integrated with high- $T_C$  magnetometers is planned in FY 1998.

## RESULTS

Major advances in niobium (Nb) thin-film fabrication technology have been developed in conjunction with this project to provide, for the first time, high quality low frequency SQUID-based magnetic sensors utilizing Nb-AlO<sub>x</sub>-Nb tri-layer technology on a 5" scale. This work has led to the production of a totally unshielded TFG sensor prototype which has been successfully demonstrated in high magnetic-field operation subjected to high levels of electromagnetic interference. The Advanced Liquid Helium Dewar (ALHD) was developed to assure that the dewar would not limit sensor performance. It has demonstrated temperature stability in motions typical of tow operations on the order of 1 mK/Hz<sup>1/2</sup> at 0.1 Hz, a factor three orders of magnitude better than for the preceding generation SGMS dewar [2]. The design of a fully populated 5-channel gradiometer to provide performance of 0.2 pT/m-Hz<sup>1/2</sup> at 0.1 Hz in mobile operations has been established based on the developments in thin-film niobium technology, advanced FLL electronics, and the ALHD and results from the evaluation of the TFG sensor prototype.

A number of high- $T_C$  magnetic sensing circuits have been developed in conjunction with this project. This included a report of 0.026 pT/Hz<sup>1/2</sup> at 1 Hz for a 2x2-cm magnetometer, the basis for the magnetometers to be utilized in the HTSG prototype under development [1]. A 3-axis magnetometer prototype has been developed and is now available as a commercial product from Conductus. It features (1) sensitivities in field operation of 0.14 pT/Hz<sup>1/2</sup> at 1 Hz, a factor of 50 better than typical performance from a commercial fluxgate, (2) reliable performance of the cryogenic circuits, (3) a long hold-time, compact dewar, and (4) miniaturized electronics with a laptop PC replacing commonly-used benchtop electronics to provide highly automated, versatile, user-friendly control and data acquisition [2], [3], [12].

The design of a HTSG concept has been established. This includes the design for a nitrogen cooling unit with a 17" diameter and 30" length and with a cryogen hold time of 33 days and a temperature stability of 10<sup>-4</sup> Kelvin/Hz<sup>1/2</sup> at 0.1 Hz [1], [2]. (This represents a reduction of 2 in volume and an increase of 8 in hold time in comparison to the ALHD.) The dimensions of this concept for a nitrogen-cooling unit could be reduced down to 12" in diameter and 18" in length without a loss of sensitivity (although there would be losses in hold time). Substantial decreases in size are projected given more aggressive design approaches.

## IMPACT/APPLICATIONS

The U.S. Navy has pioneered the 5-channel tensor-gradiometer approach for enhanced magnetic target detection, classification, and localization and the technology area of superconducting magnetic sensors for long-range detection in mobile applications. The Navy has demonstrated the utility of these sensors for the long-range detection of underwater targets in the MADOM ATD. The Navy's program has supported development of the first commercial dc SQUIDs, electronics to suppress low frequency noise and to provide ultra-wide bandwidths, and large-scale niobium thin film devices for unshielded operation. Investments by

this project have supported substantive refinement in high- $T_c$  magnetic sensor technology. The ALHD represents a major advance in dewar technology for a number of applications requiring a high degree of thermal and magnetic stability at cryogenic temperature. It provides the basis for the concept of a high performance, compact nitrogen-cooling unit for the HTSG.

## TRANSITIONS

One low- $T_c$  sensor technology transitioned to the MADOM 6.3 Advanced Technology Demonstration in FY 1989 and to the Buried Mine Detector (BMD) 6.4 Program in FY 1992. Although the BMD Program is not currently funded, the advanced HTSG prototype from this project is projected to transition to the Remote Mine Hunting System (RMS). The low  $T_c$  TFG and the HTSG technology may also be transitioned for nonacoustic ASW demonstrations as required by ONR or PMA264 and for international collaborations with Japan and the United Kingdom. The approach developed in this task can be applied to environmental cleanup, geophysical surveys, the location of underground or undersea cables, the detection of underground facilities, archeology, and treasure hunting. In particular, the low- $T_c$  technology from MADOM has been successfully demonstrated in the FY 1995 Feasibility Demonstration of the Mobile Underwater Debris Survey System (MUDSS) and will be utilized in the FY 1998 Technology Demonstration of MUDSS [2]. The nitrogen-cooled HTSG will be utilized in subsequent surveying for UXO cleanup and related applications.

## RELATED PROJECTS

This 6.2 exploratory development project has been supported by a contract to IBM Research sponsored by ONR 312 (Dr. D. van Vechten) and CSS Internal Research to investigate noise mechanisms in high  $T_c$  SQUID magnetic sensors. The Phase II SBIR to Conductus, Inc. sponsored by ONR 322 (Dr. J. Kravitz) has contributed directly to developments described in this report. The project has also been supported by the VSW Integrated Sensors Project at CSS sponsored by ONR 321 (Dr. R. Jacobson) to investigate approaches for platform magnetic-noise reduction in mine hunting vehicles.

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